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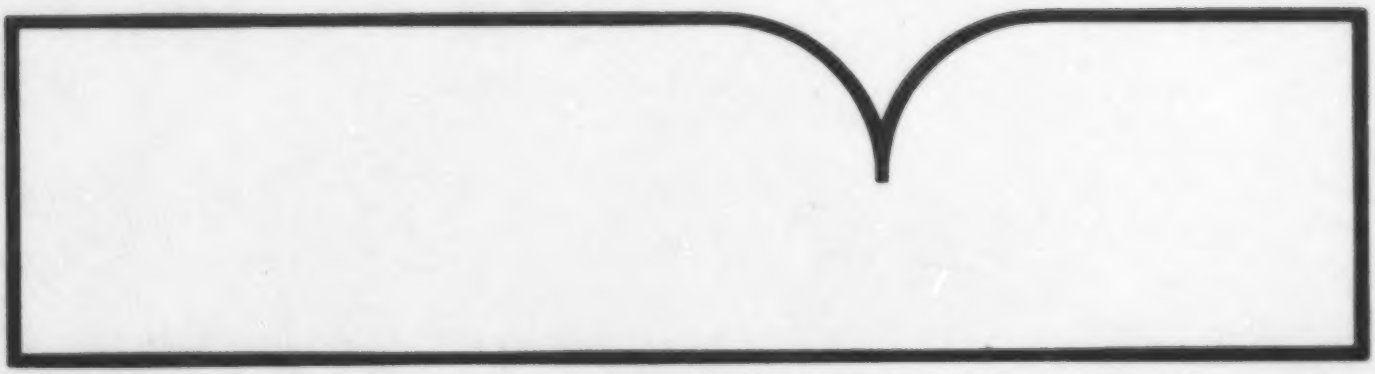

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NORTH AMERICAN AND EUROPEAN EXPERIENCE WITH BIOLOGICAL TOILETS

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ABSTRACT

A history of North American and European experience with biological toilets is provided. The early use of these devices in Scandanavia was to solve a specific problem, that of providing a low-cost solution for disposing of human wastes from recreational cabins. Because of their environmental attractiveness their popularity increased rapidly and their marketing area was widened to include year-round use. These same factors resulted in closer scrutiny by both Scandanavian and American agencies in the form of controlled and field testing programs. The results of these tests have been improved designs and understanding of the viable applications of these devices, which are significantly more limited than first implied.

KEYWORDS

Human wastes; biological toilets; composting toilets; waterless toilets; blackwater.

INTRODUCTION

Although composting of organic matter has been occurring since the very beginnings of life on earth, the concept of a toilet to biologically decompose or stabilize human wastes directly in a controlled container or reactor is relatively new. The original "mouldering" toilet design and installation is credited to Rickard Lindstrom of Sweden in 1939. However, the system was not publicly described until 1964.

In 1973, when biological toilets were being introduced to the United States, it was indicated by manufacturers that over 1,300 Scandanavian "homes" had installed biological toilets. The unfortunate use of this term, implying year-round installations, marked a deviation in marketing strategy for these units which was to have major implications. Almost all of those 1,300 installations were in recreational cabins, used 45 to 50 days each year, as an alternative to the more expensive and often infeasible septic tank-soil absorption systems and to the less desirable outdoor pit privy (Guttormsen and Pedersen, 1978). The result was that the biological toilets were marketed in the U.S. primarily for year-round use, while the technology experience was based almost exclusively on limited seasonal use.

Scandanavian authorities, concerned about the rapidly expanding use of these facilities in recreational cabins and the marketing expansion for year-round installations, initiated a testing program in 1973 in which 21 commercial biological toilets were studied under controlled conditions. This study was followed by a field demonstration project with seasonal and year-round dwellings equipped with biological toilets. The result of these studies was the development of a standardized testing program for these devices in 1981 whereby proprietary devices can receive approval for use in either vacation or permanent homes, with a capacity limitation

for each use (Molland, 1984). Because of the positive attitude maintained by their governments toward the use of biological toilets as alternatives to primitive body waste disposal and expensive or infeasible septic tank-soil absorption systems, the biological toilet market has grown to about 4,000 units per year in Norway in 1982, but the number of competing devices has drastically diminished to reflect the tested and approved models (Molland, 1984).

During this same period the U.S. market has gone through an initial period of significant sales, followed by a reduced sales period. The initial period was characterized by an aggressive marketing approach which both failed to acknowledge several technological shortcomings and scientific gaps and appealed to the significant numbers of ecologically sensitive individuals with only a minimum of knowledge of the technical and sociological issues concomitant to the use of these devices. Although some research was eventually initiated to determine the proper and safe use of biological toilets in the U.S., no major governmental consumer-protection efforts comparable to the Scandanavian program was feasible. The second phase of the U.S. experience has resulted from limited U.S. testing, secondary information dissemination from the Scandanavian testing, and a reaction to the poor results of early biological toilet installations. In 1981, the number of biological toilets installed in the U.S. was estimated to be about 5,000, while over 30,000 were claimed for Canada, and another 30,000 in 20 other countries (Smith, F.W., 1981).

An interesting twist on the original application concept has been occurring in the U.S. That variation is the use of the large types of these devices for recreational and military use. The U.S. Forest Service and other nature-oriented organizations have several installations in locations which are generally inaccessible by vehicles, e.g., hiking, backpacking, and large park facilities (Cook, 1981; Smith, M.E. 1981). Also, the U.S. Army Corps of Engineers has been conducting studies of large composting toilets for remote locations which must periodically accommodate large numbers of troops. In these unusual applications the biological toilet provides two valuable improvements over the traditional methods, i.e., waste containment and some decomposition or stabilization.

BIOLOGICAL TOILET CONCEPTS

The definition of a biological toilet has been revised often since its inception. A reasonable definition is that a biological toilet is a system which accepts feces, urine, toilet paper and possibly other dry organic wastes, eliminates excess liquid and aerobically decomposes the solid material to a humus-like product. Molland (1984) emphasized that a biological toilet for year-round home installation must evaporate all excess moisture, but the large recreational/military applications in the U.S. rely on drainage of excess liquid to perform their function. Early definitions of large biological toilets were quite unclear and emphasized the "natural" ability of the unit to perform evaporation and to biologically decompose even in very cold winters. In fact one of the most difficult problems in defining biological toilets is the extreme variety of designs available and their varying principles of operation. However, all biological toilets must accept body wastes and must eliminate excess liquid to perform aerobic stabilization of solids to humus.

The taxonomy of biological toilets is first broken into two groups by size. Within the large group a variety of approaches have been used, but the two most common are a sloping floor continuous unit and a rotating-chamber batch unit. Small units all employ fans, heating elements and mechanical mixers, while these features are optional on large units depending on their application. Conceptually, the feed material includes human body wastes, bulking agent, and all associated organisms, pathogenic and nonpathogenic. Oxygen (aeration), mixing, energy, ventilation, and time to complete the evaporation and allow some degree of biological decomposition are provided in the toilet structure. The humus-like product, if the reaction has been provided sufficient time, should resemble soil in appearance and odor and contain reduced levels of pathogens. Since the toilets used in the U.S. for recreational/military installations are designed for waste containment, odor minimization is accomplished by draining excess liquid to assist the inadequate evaporative capacity of the unit. This approach may lead to some aerobic biological decomposition if evaporation succeeds in reducing the pile moisture to acceptable levels. This can happen only if use patterns are sufficiently far apart, but will not if continuously used at a rate greater than the evaporative capacity. The remaining discussion will be concentrated on biological toilets suitable for individual home use.

The overall solids content of human body wastes is generally less than 10 percent. Without a bulking agent and sufficient loss of excess moisture, biological action would be anaerobic, giving off few calories, e.g., 26 kcal per gram-molecule of glucose, for assisting evaporation

and raising pile temperature and producing offensive gases such as hydrogen sulfide. This form of biological action is much slower than the aerobic form and is generally undesirable. Aerobic degradation of the organic matter provides far more energy for evaporation and heating, e.g., 484 to 674 kcal per gram-molecule of glucose, and requires a moisture content from 40 to 70 percent to be present in the pile. The 70 percent limit, above which the air cannot normally circulate throughout the pile, is an absolute maximum. The actual upper limit is a function of the waste matter and the bulking agent employed (Golueke, 1976). Therefore, the generally quoted limits for best operation are 40 to 60 percent moisture. Since drainage of excess liquid and absorption of excess liquid by bulking agent are limited measures, Molland (1984) defines the biological toilet's two major functions to be evaporation of excess water and degradation of solid (organic) materials. He rejects the commonly used term "composting" for the latter function because the energy produced by 85 to 90 percent reduction of organic material would account for only 30 percent of the energy required for evaporation of the excess water in the human wastes. Approximately 1 liter of liquid would need to be evaporated at 600 kcal l^{-1}, while 50 percent destruction of volatile solids (~ 40g) under aerobic conditions would yield about 5.46 kcal g^{-1} destroyed. Therefore, the evaporation requires about 600 kcal, and the energy released is less than 1/2 of that. The heat loss from the evaporation reduces available energy for temperature rise of the solid mass, which is generally too small, i.e., high surface to volume ratio, to reach high (lethal) temperatures.

Temperature of the mass has also been confused since the introduction of these toilets. After extensive testing it became clear that the temperatures reached in large biological toilets were only minimally above ambient conditions. This lower temperature biological decomposition relies on unfavorable conditions and time to provide for the destruction of pathogenic organisms. Successful accomplishment of that goal is inherently dependent on elimination of short-circuiting in the reactor. In small biological toilets the need for accelerated action required the use of heaters and forced ventilation from their inception, while larger units initially relied on natural ventilation and heating. These units have now been commonly equipped with heaters and fans in northern installations to assist the inadequate natural processes for year-round operation.

Much was made in the early literature of the importance of the carbon to nitrogen (C/N) ratio, before it was discovered that excess moisture elimination was the critical step in successful performance (Molland, 1984). The low C/N of human body wastes (6-10) should be increased through the addition of other household or yard/garden wastes (bulking agents) to avoid the production of ammonia from the mass, which can be offensive both to users and to numerous creatures, such as mites, which may crawl up the chute to the seat (D'ndal, 1980). The ammonia produced may have some beneficial effects in reducing certain viral and bacterial species however. However, a C/N between 20 and 30 is considered optimal, producing a minimum of ammonia and having the proper balance of nutrients for maximum rate of decomposition. Given the broad range of C/N for process requirements, this variable is not normally critical to biological decomposition, and the amount of bulking agent required for maintaining porosity of the mass is the governing factor.

Another factor which was confused by the early literature was the level of decomposition to be expected. Much was made of the small amount of humus produced per user per year. As noted above, the average body waste production of an individual is approximately 1,100 to 1,600 g d^{-1}. Of that, dry solids constitute between 5 and 10 percent. Conversely, the moisture content is 90 to 95 percent. Of the approximately 100 g of dry solids, about 83 percent are organic in nature. Nutrient content of the solids is about 12% nitrogen, 3.9% phosphorus (as P_2O_5), and 2.8% potassium (as K_2O) (Gotaas, 1956). Theoretically, drying to 50 percent solids would reduce the total weight of wastes to about 220 g d^{-1} per person. If bulking agent were included, evaporative losses as a percentage would be reduced to a lower value, but would still be dominant. If biological degradation were to occur, the proportion of organic matter would reduce and other constituents would change depending on their reaction involvement and physical state. Without a totally controlled study any simple measurement of ash content of the final product is without meaning.

One of the major issues in any discussion of biological toilets is the end product. Although originally purported to be a safe humus or soil-like material, there has been a general reluctance to use it haphazardly on the garden. One American study which specifically measured pathogenic content of the humus established that the variable performance of these units resulted in an end product which was not normally suitable for other than burial around shrubs and other non-edible ornamental plants (Enferadi, et al, 1985). In this study end products of poorly operating biological toilets showed positive results in screening tests for specific pathogens, parasitic, bacterial and viral. Systems which more closely approached their

functional goals were found to occasionally exhibit positive samples for parasites only, a fact consistent with the assessment of Feachem, et al (1981), who noted that parasites would be the only form likely to survive a lengthy containment period in a continuous biological toilet.

The issues of low-temperature biological degradation and pathogenic destruction were the source of much confusion in the early years of marketing these toilets. The term "composting toilets" generally implied high-temperature destruction of both organics and pathogens in the sanitary/ environmental vocabulary. However, the biological toilets were quickly found to be operating at lower temperatures with claims of a hygienically safe product. It has been shown (Salkanaja-Salonen, 1984) that survival of pathogens is reduced in composters when compared to soil at the same low temperatures due to environmental conditions more unfavorable to their survival, if all other factors are the same.

PERFORMANCE STUDIES

There were no uncontrolled tests of the performance of biological toilets before 1977, and almost all of the information on these devices was directly or indirectly produced by manufacturers. A typical source was from Nichols (1976) who analyzed final solids from seven large, sloping-floor Swedish toilets for bacteria and found that the most predominate forms of bacteria were of the family Bacillacae, less than 2 percent of the colonies were pathogenic organisms from the genera Listeria, Klebsiella, Staphylococcus, Salmonella, Proteus and Pseudomonas, and no colonies of Escherichia coli. The time lapse between sampling in Sweden and U.S. analysis was not noted, nor was the sample preservation technique. Valdmaa (1974) analyzed small toilets and found average temperatures in the pile to vary between 29 and 34°C and noted the final product from 8 units to have the following characteristics: volatile solids 48%; nitrogen 2.6%; phosphorus 1.5%; and fecal coliform <10 to $>10^5$ g^{-1}.

Similarly, other positive laboratory results were produced by manufacturers which showed quality product materials, but lacked detail on units sampled, sampling procedures, and sample preservation techniques. Several of these studies inadvertantly showed the presence of anaerobic conditions, excess liquid buildup, and short-circuiting.

A third-party field test of this period was performed in Canada by McKernan and Morgan (1976). This study was performed in northern Manitoba Province where exceptionally high diarrheal rates were endemic in communities where human waste disposal systems were primitive. Large sloping-floor units required pumping of excess liquid accumulations, (2 of 3 units), used about 1.5% of the total household electric power demand for heating and ventilation, reached a maximum pile temperature of only 19°C, and had some odor and fly problems. The small toilets were unable to handle extra loads from guests (excess liquid), had severe odor problems, and suffered structural defects in seals, stirring mechanisms and heaters.

In reviewing experience in the state of Maine with these units over the period 1974 to 1977, Hoxie and Hinckley (1978) noted that financial institutions were reluctant to make loans to people planning to use biological toilets owing to the uncertainty of their subsequent market value. They also suggested the need for public education programs, toilet design improvement and a testing program for these units.

In the mid-1970's the Norwegian government initiated a large controlled study of the biological toilets commercially available in that country. The results of this first large-scale controlled study were disseminated throughout the world and had a profound effect in "legitimatizing" the biological toilet beyond the borders of Scandanavia. Units were housed in a greenhouse at a temperature of about 17°C for the 150-day test period, and they were loaded with weighed portions of human wastes and kitchen scraps for the first 50 days, simulating cabin usage. Loadings to large toilets corresponded to 6 people and to small toilets, 4 people. Weight reduction, temperature in the pile, E. Coli concentrations and Salmonella tel-aviv and poliovirus survival were recorded. The results were broken down by classification of biological toilets (Guttormsen, 1978; Guttormsen and Pedersen, 1978). Six large box-type units with volumes of 1,200 to 1,600 liters were found to provide poor evaporation resulting in mostly anaerobic decomposition and excess liquid accumulation. None of these toilets were considered acceptable in terms of final humus quality two months after loading.

Two of six large sloping-floor toilets tested were somewhat more successful in terms of weight reduction (>70%) and visual assessment of humus quality two months after loading ceased. One of these two units employed a fan, while the other had superior natural

ventilation. These units vented 20 and 19 ls^{-1} of moist air, respectively, resulting in better evaporation, which accounted for most if not all of the improved weight reduction. Pile temperatures were all below 22°C. Also, urine accumulation was common at the outlet chamber due to short-circuiting down the sloping floor.

Six small toilets with heating elements and fans also were tested at the lower loading. Weight reductions were all between 72 and 91 percent, and final humus quality was visually judged satisfactory to good in four of the six units two months after loading ceased. Maximum power draw varied from 0.16 to 0.28 kW, and resulting solids temperatures were all below 26°C, with the exception of one unit which reached 55°C. Only two units vented more than 9 ls^{-1} of air from the chamber. Small toilets without fans and heating elements were judged inappropriate to functionally address the need.

Several other observations of interest can be made from the cabin testing program among these are:

- Temperatures rose initially due to the great mass of starter material (peat) to waste, reduced to nearly room temperature during the remainder of the loading period, and rose again in the larger units after loading ceased and evaporation caught up with excess liquid accumulation.
- A wide range of E. coli reduction occurred during the loading period. After loading ceased and evaporation reduced excess liquid accumulations, reductions of E. coli to less than 10^2 per gram of humus was universal.
- Inoculation with Salmonella Tel-aviv and poliovirus type I resulted in elimination of these organisms in all but one case in less than four weeks.

The latter portion of this Norwegian testing program attempted to deal with the issue of the applicability of the biological toilets for permanent residences (Guttormsen and Pedersen, 1978). The results were not widely distributed, and did not provide much quantitative evidence of their applicability to permanent dwellings. However, the authors did note several key facts about biological toilets: heaters and/or fans were required to provide sufficient capacity; user maintenance was vital to successful performance; humus product was not safe for garden use; and fly problems would occur without the use of pesticides.

Full-scale year-round installations of biological toilets in certain areas of the U.S. and Norway were subsequently reviewed. In the State of Oregon, 15 of 23 users reported fly problems and 16 of 23 reported excess liquid buildup (Kreissl, 1982). The former were controlled primarily by pesticides, while the latter was generally controlled by drainage. Fifteen of 17 responded that odors were present, most noting the odor inside the home and outside near the vent pipe. Norwegian field studies resulted in similar problems, inadequate liquid evaporation capacity, subsequent odors, flies and complicated care and maintenance. A comprehensive study in California (Enferadi, et al, 1985) found similar problems, i.e., 8 of 10 large sloping-floor units experienced fly problems and excess liquid buildup and small units exhibited similar liquid buildup problems in addition to universal odor porblems. The California study included a detailed study of vectors, screening for parasitic, bacterial and viral pathogens, and analyses of accumulated excess liquid. Accumulated liquids were found to contain anywhere from 20 to 88,000 mg l^{-1} of suspended solids (SS), chemical oxygen demand (COD) concentrations from 240 to 60,000 mg l^{-1}, and the following pathogens:

- parasitic forms - ciliates, cysts, eggs, larvae, and flagellates
- bacterial genera - Proteus, Enterobacter, Citrobacter Klebsiella, Aeromonas, Yersinia, Hafnia, and Providencia
- viral - Reovirus

Vector studies found a variety of mites, fly larvae, and beetles in all units. No spiders harmful to humans and no cockroaches were found. Gnats, most small flies and mites, and the beetles found were considered to be of minimal significance as vectors. The most significant vectors were the larger houseflies which were found in most of these toilets. There numbers, however, were not excessively large and were considered controllable "by the dedicated user". It was concluded that the total exclusion of arthropods from these toilets was not possible, nor necessarily desirable. Good fabrication and installation practices were recommended to minimize the problem.

Based on the Scandinavian studies the Norwegian and Swedish authorities established a certification program for biological toilets in 1981. The testing program evaluates the installation instructions, soundness of construction, care and maintenance requirements, capacity, quality of degraded material (humus) and odor. The tests require 22 weeks in a controlled temperature and humidity environment with instrumented waste loading and exhaust air ventilation measurement. As of August, 1983, only 3 of 7 tested units for year-round use and 9 of 12 for seasonal use had been approved, and each of the approved units underwent some degree of required change during the test in order to pass (Molland, 1984).

The three units thusfar approved for year-round usage all employ heating elements and fans. Two are small units with capacities of 2 and 3 persons requiring emptying of solids every 3 and 2 weeks, respectively. The other is a large rotating batch unit for 5 people requiring emptying of one compartment (4 total) every 3 months. All three of these toilets are also approved for seasonal use as well. In the case of the small units their capacities are identical owing to the short time required before emptying the solids. However, the large unit is rated at a capacity of 8 persons (with a one-year emptying cycle) in cabin usage, as opposed to 5 in year-round use. Also, the same unit has a capacity of 2 persons in cabin use without the fan and heating element (Molland, 1984). One last item of interest is that approved year-round units must have sufficient evaporative capacity to avoid excess liquid accumulation, while cabin or seasonal units can utilize drainage of excess liquid. Finally, it is enigmatic that the original continuous biological toilet concept, i.e., the large sloping-floor design, has not been found acceptable due to short-circuiting of liquid and inadequate mixing of the pile.

DISCUSSION

The present situation in North America and Europe reflects several socio-economic and technical factors. Foremost among these is the fact that newer units represent attempts to overcome the technical shortcomings of older systems. The primary example of this is the greater evaporative capacity of new biological toilets. As an example Guttormsen (1980) illustrated that to properly service (aerobically degrade the wastes of) 4 people a biological toilet must evaporate about 4.2 ld^{-1}. Given that humidification of air is a cooling process and the amount of excess water is substantial in human wastes, the need for more powerful fans and heaters is quite understandable. With proper toilet design the greater ventilation capacity also provides the necessary oxygen to the aerobic organisms to efficiently carry out their degradation of organic matter. Since the excess water must be evaporated to initate the aerobic degradation, these two primary functions are quite compatible, even though sequential. When the pile moisture is reduced to about 70 percent, effective biodegradation can begin.

The idealized description above also assumes that the addition of kitchen, garden or lawn scraps (carbonaceous bulking agents) and/or other mechanical means are provided to ensure proper air flow through the pile to optimize the effectiveness of both evaporation and biological decomposition. If these conditions are met, the often-debated factors such as C/N and pH are of minor interest, serving only to cloud the primary issues. Also, the above description provides a basis for evaluation of prior experience and philosophies of operation.

The result of the new more mechanically dependent designs is that they still require knowledgeable operation and also require significantly increased power. If the Scandanavian-certified toilet for 5 persons is employed at capacity, the fan and heater would be expected to draw about 6 kWh per day. At 10 cents per kWh the annual operating cost for a year-round installation would be about $200.00. The homeowner would be expected to empty a chamber every three months and provide continuous addition of bulking agent. Also, the capacity for temporary overloads due to social occasions is limited.

U.S. experience with greywater disposal systems has repeatedly shown that greywater (sullage) both constitutes about 2/3 of the total wastewater generated by a typical rural house and contains pathogens. After septic tank treatment greywater has nearly identical properties to combined wastewaters, and is best disposed of by conventional soil absorption. In cases where some non-potable reuse is desired, sand filters and disinfection are the most practical and reliable methods of treatment. With the need for these greywater treatments, the economics of these systems are not competitive with more conventional systems which treat and dispose of the entire household wastewater, except in areas where soils are not capable of safely infiltrating the wastewater. Therefore, except for that fraction of the population which perceives complete recycle of wastes as a goal unto itself, the market for biological toilets appears limited to those locations where either water supplies are severely limited or soil

absorption is not feasible.

Small biological toilets generally cost about $1,000 or more, while larger units can cost more than $4,000. Installation costs are not included. Operating costs may range from essentially nothing for purely natural designs to $200 per year, assuming the users provide the necessary daily maintenance of adding proper amounts of bulking agent, mixing where and when required, and the periodic removal and burial of the humus product. In contrast, a septic tank-soil absorption system (ST-SAS) can be expected to have a similar initial cost and the capability of handling the entire wastewater from the dwelling. Operational costs for 5 persons would be in the range of $50 per year, including the cost of water and septic tank pumping.

Much has been said in the Norwegian papers (Guttormsen, 1978; Guttormsen and Pedersen, 1978) about the biological toilet coming closest to fulfilling the ideal toilet criteria provided by the Wagner and Lanoix (1958): no contamination of soil surface; no contamination of ground water; no contamination of surface water; excreta not accessible to flies or animals; no or minimal handling of fresh excreta; no odors or unsightly conditions and have simple and inexpensive construction and maintenance.

Clearly, the above description would represent an ideal solution for much of the world's population. By definition the biological toilet, if structurally sound, should fulfill the two non-contamination of water requirements. If the process functions properly with adequate heating and ventilation and the final product is buried near trees and non-edible crops, the soil surface protection, odor minimization and recycle of nutrients criteria can also be fulfilled. Although fly access may be minimized and the final humus product is greatly improved when compared to fresh excreta, both of these criteria are only partially fulfilled. Commercial biological toilets are quite expensive, even by North American and European standards, however, and the level of user maintenance is both significant and crucial to proper functioning of these systems (Gurak, 1977; Mara, 1982; Kalbermatten, et al, 1982). Therefore, the low-cost and simple maintenance criteria cannot be met by these systems. It is reasonable to assume that in warmer arid climates low-cost, home-built biological toilets may be feasible, but the required maintenance problems and the resulting deleterious performance in other categories could limit the application of these systems as well.

CONCLUSION

Biological toilets were originally designed to solve a specific problem, the sanitary disposal of human wastes in recreational/seasonal cabins in rural areas of northern industrialized countries. Overzealous marketing of these units as replacements for flush toilets in year-round homes and urban areas resulted in several unsatisfactory installations. Although a small continuous market exists for ecologically sensitive individuals who are willing to accept the aesthetic and maintenance problems and for the original seasonal/cabin applications where the only alternative is less aesthetic and more primitive, the biological toilet has not been widely accepted. Improved designs being approved by the Scandanavian countries are more expensive to purchase and to operate, mitigating their original appeal which was their low-cost and simplicity. In essence, biological toilets are, like any other technology, a tool which has a certain limited applicability, and like any other waste management tool is an appropraite choice where ST-SAS's are not feasible and simpler latrine systems are not desirable or acceptable. They share this portion of the market with such devices as incinerating toilets, which are more energy-intensive and expensive to operate and provide no opportunity for nutrient recycling.

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